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NIR/Optical Selected Local Mergers — Spatial Density and sSFR Enhancement

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Abstract. Mergers play important roles in triggering the most active objects in the universe, including (U)LIRGs and QSOs. However, whether they are also important for the total stellar mass build-up in galaxies in general is unclear and controversial. Answer to that question depends on the merger rate and on the average strength of merger induced star formation. In this talk, I will review studies on spatial density and sSFR enhancement of local mergers found in NIR/optical selected pair samples. In line with the current literature on galaxy formation/evolution, special attention will be paid on the dependence of the local merger rate and the sSFR enhancement on four fundamental observables: (1) stellar mass, (2) mass ratio, (3) separation, and (4) environment.

1. Introduction

Historically, galaxy mergers were associated with “pathological galaxies” (Shapley 1943) that did not fit into the “Hubble Sequence”. Simulations of Toomre & Toomre (1972) established firmly the connection between gravitational tidal effects during galaxy merging and morphological features such as long tails, bridges and plumes, seen abundantly in “Atlas of Peculiar Galaxies” (Arp 1966). Later studies found evidence for mergers to play important roles in triggering extreme starbursts (such as ULIRGs, Sanders & Mirabel 1996) and QSOs (Heckman et al. 1986; Sanders et al. 1988; Bahcall et al. 1995). Alar Toomre (1978) proposed that merging can transform spirals into ellipticals, a theory that put mergers to the center stage of galaxy evolution. In the hierarchical structure formation paradigm of the contemporary cosmology, galaxy and dark matter halo (DMH) merging is one of the most significant processes affecting the evolution of structures in the early universe, and is largely responsible for the growth of massive dark matter halos and the buildup of galaxies (Kauffmann et al. 1993; Lacey & Cole 1993; Khochfar & Burkert 2005). In cosmological simulations, it is often assumed that merger induced star formation (SF) is the major (or even the dominant) contributor to the high star formation rate (SFR) at $z \sim 1 - 2$, the epoch when the net SFR in the universe peaks (Guiderdoni et al. 1998; Somerville et al. 2000; Baugh et al. 2005). On the other hand, observationally, we are still facing two unsettled questions: (1) how many galaxies are involved in mergers? (2) is there any significant SFR enhancement in an average merging galaxy (which is very different from FIR selected mergers such as ULIRGs)? In this talk I will review the literature on studies of these two topics for local mergers ($z \lesssim 0.1$). Studies for mergers of higher redshifts will be covered elsewhere in this conference.

2. Merger Fraction in the Local Universe

Mergers are selected either by counting galaxies in close pairs that are destined to merge, or by identifying peculiar galaxies with morphological features associated to mergers. Generally, the former selects early stage mergers when the two galaxies are still visually separable, and the latter favors later stage mergers (or even post-mergers) because the tidal features are fully developed until several 10^8 years after the first close-encounter, and lasts well after the coalescence (Barnes & Herquist 1996). A summary of results on the local merger fraction f_{mg} is listed in Table 1.

Table 1. Results on Local Merger Fraction f_{mg}

reference	method	selection	μ_{max}	r_{max} $\text{h}^{-1} \text{ kpc}$	Δv_{max} km sec^{-1}	N_{mg}	f_{mg} %
Fried (1988)	morph	$B < 12.0$	...	...	...	3	3
Xu & Sulentic (1991)	pair	$m_{\text{Zw}} \leq 15.6$	...	...	1000	921	10
Patton et al. (1997)	pair	$m_{\text{ph}} \leq 14.5$	...	20	500	130	4.3 ± 0.4
Patton et al. (2000)	pair	$-21 < M_{\text{B}} < -18$	...	20	500	80	2.3 ± 0.5
Xu et al. (2004)	pair	$K \leq 12.5$	2.5	20	500	30	1.7 ± 0.3
Bell et al. (2006)	2pcf	$M_{\text{star}} > 2.5 \times 10^{10} M_{\odot}$	...	21	...	...	1.1 ± 0.2
de Propris et al. (2007)	pair	$-21 < M_{\text{B}} - 5 \log h < -18$	...	20	500	112	4.1 ± 0.4
Kartaltepe et al. (2007)	pair	$M_{\text{V}} < -19.7$	...	20	500	90	0.7 ± 0.1
Patton & Atfield (2008)	pair	$14.5 \leq m_{\text{r}} \leq 17.5$	2.0	20	500	473	2.1 ± 0.1
Domingue et al. (2009)	pair	$K \leq 12.5$	2.5	20	1000	265	1.6 ± 0.1
Robaina et al. (2010)	2pcf	$M_{\text{star}} > 5 \times 10^{10} M_{\odot}$	...	21	...	...	1.4 ± 0.2
Darg et al. (2010)	morph	$M_{\text{r}} < -20.55$	3.0	...	500	1243	3.0 ± 1.5
Xu et al. (2011)	pair	$K \leq 12.5$	2.5	20	500	221	1.3 ± 0.1

The early result of Xu & Sulentic (1991) is high ($f_{\text{mg}} = 10\%$) because it includes wide pairs (up to projected separation of $r \sim 100 \text{ kpc}$) and both major and minor mergers. Pair samples of Patton et al. (1997), Patton et al. (2000), de Propris et al. (2007) and Kartaltepe et al. (2007) are absolute magnitude limited without any restriction on the mass ratio or the luminosity ratio. It is difficult to compare these results with any model because the mass ratio is one of the most important parameters in merger models. Also, these pair samples suffer from the “missing secondary” incompleteness, namely many paired galaxies are missed because their companions are fainter than the absolute magnitude limit. This bias is avoided in the works of Xu et al. (2004), Patton & Atfield (2008), Domingue et al. (2009) and Xu et al. (2011), who confined their samples to close major-merger pairs of projected separation $r \leq 20 \text{ h}^{-1} \text{ kpc}$ and $\mu \leq 2.5$ or $\mu \leq 2$, μ being the primary-to-secondary mass ratio ($\mu = M_{\text{pri}}/M_{\text{2nd}}$). Xu et al. (2011) is an update of Xu et al. (2004) and Domingue et al. (2009), with two major improvements: (1) a correction for the contamination of unphysical pairs caused by galaxy clustering; (2) exclusion of the local super-cluster region. The result of Patton & Atfield (2008) is higher than that of Xu et al. (2011), and the difference is more significant after adjusting the different values of μ_{max} . Both studies used galaxies taken from the SDSS database. Patton & Atfield (2008) included only pairs with both components having SDSS redshifts. This resulted in a rather low redshift completeness of $\sim 30\%$ for the pairs because of the “fiber collision” issue in the SDSS redshift survey. The large correction factor ($\gtrsim 3$) for this incompleteness may indeed introduce large uncertainties in the result. In contrast, Xu et al. (2011) included pairs with at least one SDSS redshift, and made their own redshift observations and literature searches for the missing redshifts. The completeness of this sample, only missing pairs with neither component

having SDSS redshift, is 89% (Domingue et al. 2009). Another major difference between Patton & Atfield (2008) and Xu et al. (2011) is that the former was selected in the optical r-band while the latter in the NIR K-band. The merger induced SF may indeed boost the L_r (which includes the H_α emission) of paired galaxies and in turn boost the f_{mg} for a given L_r because of the steep decline of the luminosity function. On the other hand, dominated by the emission of old stars, L_K is insensitive to the enhanced SFR.

The apparently good agreement between the early result of Fried (1988) and the recent result of Darg et al. (2010) for morphologically selected mergers is fortuitous. The sample of Fried (1988) includes both major mergers and minor mergers, while that of Darg et al. (2010) includes only the major mergers ($\mu \leq 3$). Excluding peculiar galaxies that cannot be resolved into two galaxies, the sample of Darg et al. (2010) is incomplete for morphologically selected mergers. Nevertheless, the agreement between merger fractions derived using morphologically selected merger samples and using close pair samples ($r \leq 20 \text{ h}^{-1}\text{kpc}$) is remarkable, indicating that the merger time scales for these two different selections may indeed be similar (Lotz et al. 2010; Conselice et al. 2009; Xu et al. 2011).

In addition to morphological and pair selected mergers, I also included in Table 1 studies based on 2-point correlation functions (2pcf). Bell et al. (2006) and Robaina et al. (2010) have shown that for massive galaxies the 2pcf can be well extrapolated down to $r = 15 \text{ kpc}$, as power-laws with $\gamma \simeq 2$. Thus, the pair fraction can be estimated from the 2pcf as following:

$$f_{mg} = 4\pi n \int_{r_{min}}^{r_{max}} [1 + \xi(r)] r^2 dr, \quad (1)$$

where n is the number density of galaxies and ξ the 2pcf. The results are indeed in good agreement with those from pair counts. On the other hand, similar to those derived using absolute magnitude limited pair samples, these results suffer from a lack of the mass ratio information.

For close major-merger pairs, Patton & Atfield (2008), Domingue et al. (2009) and Xu et al. (2011) found that f_{mg} is constant against the luminosity or the stellar mass M_{star} . Xu et al. (2004) found a positive dependence of f_{mg} on M_{star} , but that result has a large uncertainty due to the small sample size (19 pairs). Much of the discrepancies between the results derived using pairs, as listed in Table 1, can be attributed to the differences in the separation and the mass ratio. The separation dependence of f_{mg} can be derived using Eq. 1, assuming $\xi(r) = (r_0/r)^\gamma$ and $\gamma = 2$. This results in a $f_{mg} \propto r_{max}$ (assuming $r_{min} \ll r_{max}$). Xu et al. (2011) found that, within the range of $1 \leq \mu_{max} \leq 10$, f_{mg} is approximately proportional to $\log(\mu_{max})$. This suggests that there are about equal numbers of major mergers with $1 \leq \mu \leq 3$ and minor mergers with $3 \leq \mu \leq 10$, contradicting a common belief that such minor mergers are much more abundant than major mergers! Extrapolating the result of Xu et al. (2011) using these r - and μ_{max} - dependences, we have:

$$f_{mg} = 1.5\% \times \frac{r_{max}}{20 \text{ h}^{-1}\text{kpc}} \times \frac{\log(\mu_{max})}{\log(3.0)}. \quad (2)$$

According to Ellison et al. (2010), both the average separation and the average velocity difference of pairs increase with the local density n , while the average mass ratio is

insensitive to n . Xu et al. (2011) found that $90.4 \pm 2.5\%$ of K-band selected close major-merger pairs in the sample of Domingue et al. (2009), with $\Delta v_{\max} = 1000 \text{ km sec}^{-1}$, have $\Delta v \leq 500 \text{ km sec}^{-1}$.

The differential merger rate R_{mg} is the probability for each galaxy to be involved in a major merger per Gyr: $R_{\text{mg}} = f_{\text{mg}}/T_{\text{mg}}$, where T_{mg} is the time scale (in Gyr) for the merger selection (e.g. for morphologically selected mergers, T_{mg} is the time during which the tidal features are recognizable). It is worth noting that (1) because galaxy merger is a very complex process (Hopkins et al. 2010), R_{mg} , f_{mg} and T_{mg} are all functions of the redshift, stellar mass, mass ratio, separation, and other parameters; (2) for a given R_{mg} , the merger fraction f_{mg} can be different in different merger selections because of different values of T_{mg} ; (3) T_{mg} is one of the major sources of uncertainties in the calculation of merger rate; for example, for close major-merger pairs of L_* galaxies with $\mu \leq 3$ and projected separation $r \leq 20 \text{ h}^{-1}\text{kpc}$, T_{mg} ranges from $\sim 0.3 \text{ Gyr}$ (Lotz et al. 2010) to $\sim 0.9 \text{ Gyr}$ (Kitzbichler & White 2008); (4) it is important to distinguish T_{mg} from the total merging time scale that starts when a companion falls into the dark matter halo (DMH) of the target galaxy and ends when two galaxies coalesce; (5) many wide pairs ($r \gtrsim 50 \text{ h}^{-1}\text{kpc}$), in particular minor mergers, may never merge (Patton et al. 2000; Lotz et al. 2010).

3. The sSFR Enhancement in Local Mergers

It was well established and well documented that, in the local universe, the extreme starbursts such as ULIRGs are triggered by galaxy mergers (Sanders & Mirabel 1996). However, there has been a long debate on whether every merging galaxy (or, in a weaker version, most merging galaxies) has significantly enhanced SF activity, presumably triggered by the gravitation tidal effect and other effects (e.g. enhanced collision rate of gas clouds) associated with merger.

Merger induced star formation was first predicted by Toomre & Toomre (1972), and confirmed by Larson & Tinsley (1978) in a study of optical colors of Arp galaxies. Many subsequent studies of the H_α emission and FIR emission (both are SFR indicators) in Arp galaxies and in paired galaxies provided further support to this theory (see Kennicutt 1996 for a review). On the other hand, Haynes & Herter (1988) found little or no enhanced FIR emission in a sample of optically selected pairs compared to a control sample of single galaxies. In a more influential paper, Bergvall et al. (2003) reported a multi-wavelength study in which they found no significant SFR enhancement for a sample of morphologically selected merger candidates. Apparently, only some merging galaxies have significantly enhanced SFR (with ULIRGs as the extreme examples) and the others do not. **Whether the mean SFR of a merger sample shows significant enhancement depends very much on how it is selected.** Kennicutt et al. (1987) and Bushouse et al. (1988) found that merger candidates which show strong signs of tidal interactions have significantly stronger SFR enhancement than optically selected paired galaxies, the latter being only marginally enhanced (a factor of ~ 2) compared to single galaxies. Telesco et al. (1988) found a strong tendency for pairs with the highest far-IR color temperatures to have the smallest separation. Xu & Sulentic (1991) showed that the enhancement of the FIR emission of close spiral-spiral (S+S) pairs with separation less than the size of the primary and with signs of interaction is significantly stronger than that of wider pairs and pairs without interaction signs. Sulentic (1989) found that elliptical-elliptical (E+E) pairs are equally quiet in the FIR emission as sin-

gle ellipticals. Very few E's in S+E pairs are FIR bright, possibly cross-fueled by their S companions (Domingue et al. 2003).

More recently, large digitized surveys (e.g. SDSS, 2MASS, 2df, etc) enabled large and homogeneously selected pair samples. A clear anti-correlation between the specific SFR ($sSFR = SFR/M_{\text{star}}$) and the pair separation has been well established (Barton et al. 2000; Lambas et al. 2003; Alonso et al. 2004; Nikolic et al. 2004; Li et al. 2008; Ellison et al. 2008). These results also showed evidence for a threshold separation at $r_{\text{clo}} = 20 h^{-1} \text{kpc}$ (or $r_{\text{clo}} = 30 h_{70}^{-1} \text{kpc}$), beyond which significant sSFR enhancement (i.e. no less than $\sim 30\%$, Ellison et al. 2008) is not detected.

Does every star forming galaxy (SFG) in close pairs with $r \leq r_{\text{clo}}$ has enhanced sSFR? This question was addressed by Xu et al. (2010) for major-merger pairs of $\mu \leq 2.5$. They observed with Spitzer a complete sample of 27 K-band selected close major-merger pairs, including 39 spirals (classified according to the morphology) that do not harbor known AGNs. Two of their results stand out: (1) on average, spirals in S+E pairs do not show any sSFR enhancement compared to their counterparts in a mass-matched control sample of single spirals; (2) the sSFR enhancement of spirals in S+S pairs is mass dependent in the sense that significant sSFR enhancement (a factor of ~ 3) is confined to massive spirals ($M_{\text{star}} \gtrsim 10^{10.4} M_{\odot}$ for a Salpeter IMF, or $M_{\text{star}} \gtrsim 10^{10.0} M_{\odot}$ for a Chabrier IMF) while no sSFR enhancement is found for less massive paired spirals. The result (1) is somewhat surprising because, if the merger induced SF is purely a gravitational phenomenon, one does not expect the morphology of the companion should make any difference. On the other hand, as pointed out by Struck (2005), the merger induced SFR depends on two things: (i) the amount of cold gas available, (ii) the amplitude of the gas compression (as depicted by the ‘‘Kennicutt-Schmidt Law’’). Because a spiral companion and an elliptical companion of the same mass should trigger same gravitational tidal squeeze, the difference between S in S+E pairs and S in S+S pairs must be due to the difference in their cold gas abundance. Unfortunately this cannot be verified because no data are available for the gas mass in these galaxies. There are several plausible explanations for the result (2). First of all it is likely that the threshold separation for the sSFR enhancement, r_{clo} , is related to the tidal radius which in turn scales with $M^{1/3}$ for major mergers. Therefore many low mass galaxies in the sample may not be ‘‘close’’ mergers although they have $r \leq 20 h^{-1} \text{kpc}$. Secondly, according to the theory proposed by Mihos et al. (1997), low mass galaxies do not have sufficient disk self-gravity to amplify dynamical instabilities, and this disk stability in turn inhibits interaction-driven gas inflow and starburst activity. Thirdly, low mass spirals have systematically higher gas fraction ($f_{\text{gas}} \gtrsim 0.4$). Hopkins et al. (2009) pointed out that in a high f_{gas} galaxy the merger induced gravitational torque is inefficient in removing the angular momentum from the cold gas and therefore is unable to transport large amount of gas from disk to nucleus. As a consequence, nuclear starbursts (a major mode of merger induced SF) may be largely missing in the low mass spirals involved in major mergers. It is worth noting that merger samples selected in either the blue band or the H_{α} emission are biased for low mass late-type galaxies, and many of them indeed do not show significant sSFR enhancement (e.g. Bergvall et al. 2003; Knapen & James 2009).

Another interesting result of Xu et al. (2010) is a significant correlation (at 92% confidence level) between the sSFR of the two components in massive S+S pairs. This is related to the above result (1) because, apparently, a paired galaxy knows not only about the companion’s morphology, but also its sSFR! The correlation is not due to

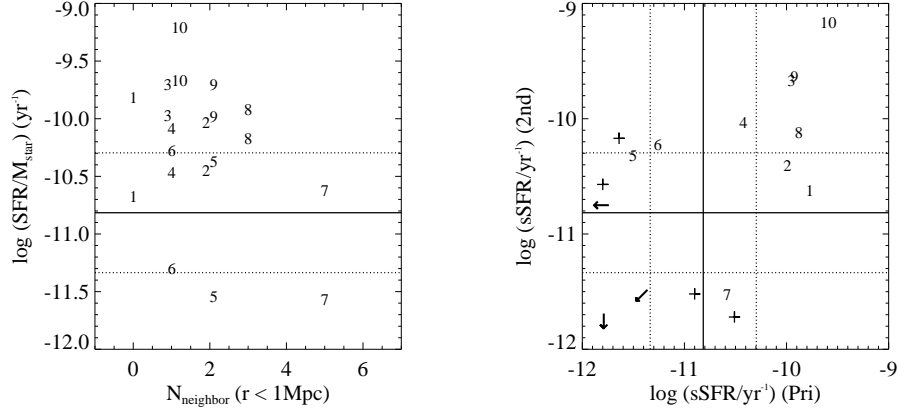


Figure 1. **Left (panel a):** sSFR vs. N_{neighbor} plot for massive galaxies ($M_{\text{star}} = 10^{10.7-11.2} M_{\odot}$, or $M_{\text{star}} = 10^{10.3-10.8} M_{\odot}$ for a Chabrier IMF) in 10 S+S pairs. The two components in each pair are marked by the same number. The solid line marks the average sSFR of single spirals in a control sample. The two dotted lines mark the $\pm 1 \sigma$ boundaries. **Right (panel b):** Plot for the correlation between the sSFR of two components in pairs. The numbers represent the same S+S pairs in panel a. The crosses and upper/lower limits are for S+E pairs. The solid lines and dotted lines have the same meaning as in panel a.

the mass dependence of the sSFR because the pairs studied have a narrow mass range of $\Delta \log(M_{\text{star}}) \leq 0.5$, comparable to that of the mass ratio of pairs ($\log(\mu) \leq 0.4$). Xu et al. (2010) did not find any significant dependence of the sSFR on the density of local neighbors within 2 Mpc radius, either. However, after reducing the radius of the neighbor searching to 1 Mpc, I did find a much more significant dependence (Fig. 1a). This is in agreement with Ellison et al. (2010) who found evidence for non-enhancement of sSFR among close pairs in high local density regions. Nevertheless, the correlation between the sSFR of the two galaxies in the same pair cannot be explained by this local density dependence because the difference between the sSFR of the two components in a given pair is much smaller than the dispersion of the sSFR of galaxies with a given N_{neighbor} (Fig. 1a). As shown in Fig. 1b, the correlation is mainly due to pairs being separated into two groups: a group of 7 S+S pairs with both components having relatively high sSFR, and another group of 3 S+S pairs plus 7 S+E pairs where at least one of the two components is a “red-and-dead” galaxy (either an elliptical in case of a S+E pair or a red S0/Sa in case of a S+S pair). Kennicutt et al. (1987) found a similar correlation between the H_{α} emission of two components in galaxy pairs (the so called “Holmberg effect”). They argued that the correlation is due to the common dependence of the SFR of both components on some orbital parameters (e.g. Δv and separation) and on merger stages. However, because having a red component is related neither to a pair’s orbit nor to its merger stage, Kennicutt’s interpretation cannot explain our result. Alternatively, I propose that the correlation is due to the modulation of the sSFR by the IGM in the dark matter halo (DMH) that the two galaxies share (being in the final stage of a merger, they have been within each other’s virial radius for $\gtrsim 1 \text{ Gyr}$). For example, when the DMH has strong “cold flows” (Dekel et al. 2009), both galaxies may have abundant cold gas supply and therefore higher sSFR. On the other hand,

DMH's containing red galaxies may have little "cold flows", and therefore starve the merger induced SF in the SFG companions. Recently, Hwang et al. (2011) reported a similar difference between the sSFR of late-type galaxies with late-type neighbors and that of those with early-type neighbors in an FIR selected sample. They interpreted the non-enhancement in latter case as a consequence of the SF quenching by the hot-gas halo associated with the early-type companion. It is not clear whether this theory applies to our result, given that some of our pairs in the lower-left corner of Fig. 1b do not contain ellipticals but red spirals, which very rarely have extended hot gas halos. Interestingly, as shown in Fig. 1a, low sSFR S+S pairs #5 and #6 are in fairly low local ($r < 1$ Mpc) density regions. Therefore the low sSFR in these two pairs might indeed be unrelated to any effect associated with the hot gas because lower N_{neighbor} usually indicates lower DMH mass and therefore lower IGM gas temperature and lower hot gas abundance.

Late-type pairs with $\Delta v \gtrsim 400$ km sec $^{-1}$, most reside in dense groups or clusters (Domingue et al. 2009), do not show any sSFR enhancement (Nikolic et al. 2004). There is no dependence of the sSFR enhancement on the orbital directions (Keel 1993).

For minor mergers ($\mu > 3$), Woods & Geller (2007) (see also Li et al. 2008 and Ellison et al. 2008) found that only low mass late-type galaxies (most being secondaries) in close pairs have significantly enhanced sSFR while massive galaxies (most being primaries) show no significant sSFR enhancement. This is exactly opposite to what Xu et al. (2010) found for major mergers. The difference is likely due to the asymmetry of the gravitational effects in a minor merger (in particular when μ is very high): for the massive primary the effects are minimal even when the two galaxies are close while for the low mass secondary the effects can be overwhelming.

Summary on merger-induced sSFR enhancement (or lack of it):

- 1) Statistically, only close mergers with separation $r \leq 20$ h $^{-1}$ kpc show significantly enhanced sSFR, while wider mergers do not.
- 2) Paired ellipticals are usually SFR quiet, same as single ellipticals.
- 3) **For close major mergers, only massive SFGs ($M_{\text{star}} \gtrsim 10^{10.0} M_{\odot}$ for a Chabrier IMF) in SFG+SFG pairs¹ in the field have significant sSFR enhancement (a factor of ~ 3). They are $\sim 25\%$ of all spirals in close major mergers.**
- 4) Spirals in close major mergers are not sSFR enhanced when they are in one of the following categories: low mass spirals, spirals in S+E pairs ("E" including red S0/Sa), spirals in dense-groups/clusters, spirals in pairs with $\Delta v \gtrsim 400$ km sec $^{-1}$.
- 5) For close minor mergers, only the low mass secondary spirals are sSFR enhanced while the high mass primaries are not.

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¹SFGs do not include the "red-and-dead" S0/Sa galaxies among morphologically classified spirals.

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